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Manipulation of Tomato Fruit Quality Through Temperature Perturbations in Controlled Environments

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Abstract. Quality factors such as size, color, taste, and nutritional content are important criteria for marketing of greenhouse tomato fruit. While the majority of the research on fruit quality factors focuses on effects of post-harvesting and storage conditions, the environmental conditions during plant growth and the time for which the fruit is allowed to ripen on the vine also influence fruit quality. Growth chamber experiments were performed with tomato (cv. Laura) aiming to study the influence of air temperature perturbations during fruit set on fruit quality at maturity, the time to harvest, and the harvest window. Plants were grown in 6" pots and pruned to the 2nd true leaf above the first fruit cluster. Nutrients were provided through a drip irrigation system. All plants were grown under the same environmental conditions except for a two week period beginning 10 days after fruit-set during which plants were assigned to one of three day/night temperature treatments, 28/23°C, 23/18°C, and 18/13°C. Five tomato fruits were harvested from each plant at three distinct physiological ages; breaker stage (taken as the point at which 25% of the fruit begins to turn red), breaker stage plus three days, and breaker stage plus six days. Harvested fruits were analyzed for mass, size, color, soluble solids content, pH, acidity, viscosity, and other quality parameters. Initial results show significant temperature effects on fruit size, mass, developmental rate, and fruit processing characteristics. The results are applicable towards the development of more efficient plant production strategies for greenhouse growers and for NASA's advanced life support research program.

Keywords. production scheduling, fruit-set, plant-production, greenhouse, controlled environment, advanced life support

Introduction

Effective environmental control is necessary for controlled environment plant production systems (CEPPS) to deliver high crop growth rates, yield, and quality according to the desired production scheduling. Traditional environmental control systems maintain levels for air temperature and relative humidity, and, in some cases, atmospheric carbon dioxide (CO_2) concentration and photoperiod extension, according to set points from grower experience or rules-of-thumb. A predictable quality and production schedule for the crop can be achieved by holding these set points throughout the growth cycle. However, this control approach is not optimal in the sense that resource costs, market conditions, and the actual state of the crop are not considered in the control decisions.

Plant production for NASA's (National Aeronautics and Space Administration) Advanced Life Support (ALS) research program can be considered a special case of CEPPS. Crops will be grown aboard future space stations for the purpose of facilitating resource recycling (including the exchange of atmospheric oxygen and carbon dioxide concentration and water purification through transpiration) and satisfying nutritional needs of the crew (Henninger, 1989). The current thinking on environmental control systems design for ALS crop production is to utilize set points that will maximize production of edible biomass. The design will follow the traditional greenhouse environmental control approach in which set points remain static throughout the growing season, but with added control over the daily light integral (Barta et al., 1999).

Alternative environmental control strategies for CEPPS have been investigated that looked at implementing control systems which synthesize information about the crop and current environmental conditions in real or near real-time. New environmental values that balance the conditions needed to optimize the crop production goals (such as flowering by a certain date or maximizing fruit quality at harvest) versus the amount of resources required to achieve those goals are identified on an hourly or daily basis throughout the production cycle. For example, strategies by Challa and van Straten (1993) and Sigrimis and Rerras (1996) integrated mathematical predictions of the plant growth and developmental status with weather and market forecasts to optimize the environmental inputs to the greenhouse on a daily basis. Phasic control, a related control strategy, adjusts environmental conditions based on particular developmental stages of the crop (Volk et al., 1997). In practice, most systems have not achieved improved production and management results primarily because there is still a knowledge gap on quantifying the dynamic relationship between plant responses and climate (Van Pee and Berckmans, 1998). More information is needed on the sensitivity of important greenhouse crops at various points during the growth cycle in response to environmental perturbations to improve control and management strategies.

Tomato is one of the most commonly grown greenhouse vegetable crops in the United States. It is also a candidate crop for the ALS program, where fruit is likely to be consumed fresh with a minimal amount of post-harvesting storage. Tomato is also an ideal candidate to study as it has been well documented that growth and development can have a strong response to changes in environment during production. For example, air temperature is known to significantly effect tomato growth and development. Higher temperatures imposed throughout a tomato crop's development usually result in shorter crop production time, but with smaller fruit and lower yield (Sawheny and Polowick, 1985; Rylski, 1979). It has been shown that the timing and magnitude of a temperature perturbation is also important. Hurd and Cooper (1970) reported that application of a short-term, two week chilling temperature on tomatoes prior to anthesis produced a delay in crop development but resulted in larger individual fruits size. Abdalla and Vererk (1968) showed that hot temperatures in excess of 30°C adversely affected anthesis and

fruit set for certain cultivars. El Ahmadi (1977) demonstrated that even a thermocycle of 26/20°C could interrupt fruit set, and a short-term exposure of 35°C severely inhibited fruit formation.

Based on this information, the period from flowering to fruit-set is a possible target for development of a temperature-based control strategy. Another possible point for application of a temperature study is the period between ten and thirty-five days following fruit-set. The rate of starch biosynthesis, which influences sink strength and thus final fruit size and yield, is highest during this period, and there may be other related processes occurring during this time that influence fruit internal and external ripening characteristics (Ho, 1996). A temperature change during this time may impact fruit maturity rate and growth through its effect on enzyme regulation.

Fruit quality measurements can be used as a second level of information in assessing the usefulness or consequence of temperature perturbation studies. The majority of studies on fruit quality parameters (those that affect taste, appearance, processing characteristics, and nutritional content) have focused on fruit ripened during post-harvest storage. However, fresh consumption of tomato fruit is the primary market for NASA and a substantial portion of the greenhouse tomato industry. Reflecting this fact, previous work has also investigated whether the quality of vine-ripened fruit exceeds that of fruit ripened during storage (Arias and Lee, 2000).

In order to determine if temperature can be manipulated in a horticulturally useful way so as to provide an additional level of control over tomato production scheduling and vine-ripened fruit quality, a series of controlled environment tomato experiments were planned. The effect of a two-week high and low temperature treatment, applied ten days after fruit-set, was evaluated on tomato fruit growth and development. Measurements of tomato fruit were made at three different stages of vine ripening to determine if there was a difference in quality due to length of the ripening period. Results from the first experiment are discussed.

Materials and Methods

Three experiments were planned of which one was completed at the time of this writing. Five EGC growth chambers (Environmental Growth Chambers, Inc., Chagrin Falls, OH), four reach-in chambers and a walk-in chamber, were used for the experiment. A Campbell 21x data logger was used for automatic recording of canopy microclimate, a re-circulating hydroponic nutrient delivery system, and atmospheric carbon dioxide control as detailed by Sauser (1998). Atmospheric conditions were logged as 15 minute averages except where otherwise noted. Nutrients were delivered via drip irrigation. The production area in each reach-in chamber was 1.2 m^2 and limited to four 1.2 m^2 production trays in the walk-in growth chamber. Chamber lighting consists of a combination of cool white fluorescent lamps that provide 95% of the incident photosynthetic photon flux (PPF) and incandescent bulbs that provided the remaining 5%.

Tomato seeds (*Lycopersicon esculentum* Mill., cultivar Laura) were sown in 76 mm (¾") rockwool cubes (Grodan, Inc., Pine, CO) and covered with a small layer of peat-vermiculite potmix (50-50). The cubes were placed in one of the reach-in growth chambers and hand-watered from above with tap water until germination occurred. A dilute nutrient solution (electrical conductivity (EC) of 1.1 mS cm^{-1}) consisting of tap water, Peter's Professional Hydrosol Formula (The Scotts Company, Columbus, OH, 5-11-26) and solution grade calcium nitrate (Hydro-Gardens, Inc., Colorado Springs, CO, 15.5-0-0) was subsequently used (2.2 g hydrosol and 1.4 g $CaNO_3$ per gallon). A 16 hour photoperiod was utilized and environmental conditions averaged 418 ±11 µmol m^{-2} s^{-1} PPF, 23.0 ±0.3 °C day / 21.7 ±1 °C night temperature

cycle, 83 ±6% relative humidity, and 637 ±137 µmol mol^{-1} carbon dioxide concentration (CO_2) at canopy height. At 14 days after sowing (DAS), 80 uniform seedlings with stem height between 5 and 7 cm were transplanted into 152.4 mm (6") green plastic pots filled with perlite (super coarse grade, Whittemore Company, Inc, Grayslake, IL) that was previously washed with tap water. Seedlings were placed so as to allow 1 cm of perlite above the top of the rockwool cube. Each pot was covered with a strip of white on black PE (polyethylene) film to prevent algae growth on the perlite surface. Pots were moved into the walk-in growth chamber, assigned to one of the four production trays at a density of 20 pots per tray at a density of 16.7 plants m^{-2}), and fitted with a drip emitter. Flexible mylar screening was erected around each production tray on DAS 24 to delineate the production area and account for side-lighting bias. At this time, 16 plants were removed (four from each tray) for destructive sampling. At the appearance of flowers (DAS 37), a hand-held leaf blower was used for 5 minutes each day to facilitate pollination. Nutrient solution was maintained at an EC of 2.1 mS cm^{-1} until flowering at which point EC was increased to 2.3 mS cm^{-1}. Water and make-up nutrient solution were added twice per week to maintain desired EC levels. Plants were pruned to a single truss, starting on DAS 39, where side shoots were removed once per week and the main stem was cut above the 2nd true leaf above the first fruit cluster.

Ten days after at least two fruits on 50% of the plants had set (DAS 56), 32 plants were removed from the walk-in growth chamber and randomly assigned to one of the four reach-in growth chambers for a two-week period. Four additional plants were removed from the walk-in growth chamber for destructive sampling. Two of the reach-in chambers were set to provide a day/night temperature cycle of 28/23°C (high temperature treatment (HT) chambers 1 or 2; HT1, HT2) or 18/13°C (low temperature treatment (LT) chambers 1 or 2, LT1, LT2). All other conditions were set to those in the walk-in chamber. Plants that remained in the walk-in chamber were kept at the control temperature of 23°/18°C (control temperature (CT) group). Actual conditions for the treatments are provided in Table 1. Mylar screening was wrapped around plants in all chambers so as to maintain a spacing of 12.7 plants m^{-2}. On DAS 70, two plants from each treatment group were randomly selected for destructive harvesting. The remaining plants were placed back into the walk-in chamber where they remained until the end of the experiment.

Fruits were removed from plants in the walk-in chamber at three different stages of maturity; breaker stage (at which 25% of the fruit showed a reddish hue), breaker stage plus three days, and breaker stage plus six days. Fruits were randomly harvested from the plants according to physiological age with only the first five fruits per cluster on each plant used for harvest. At least eight fruits were collected from each treatment group at each physiological stage. Fruits were measured for diameter and fresh weight and then immediately subjected to a series of tests for the following quality parameters: fresh mass, dry mass, diameter, moisture content, soluble solids, pH, acidity, Bostwick consistency, color, firmness, ascorbic content, and lycopene. Environmental conditions in the walk-in growth chamber averaged 447.2 µmol m^{-2} s^{-1} PPF, 23.0/17.9 °C thermoperiod, 1102.7 µmol mol^{-1} CO_2 concentration, and 84% relative humidity at canopy height for the duration of the experiment.

Results

Statistical tests were conducted to determine if there was an additional treatment effect introduced by using two growth chambers for each temperature treatment. The number of chronological days required for fruit from each plant to reach breaker stage was used to indicate whether or not there were significant differences. Results (not shown) rejected the hypothesis that there were significant differences ($\alpha = 0.05$) between chambers. Data was therefore pooled together from the respective growth chambers for subsequent data analysis.

Table 1: Environmental conditions (and standard deviations) for each growth chamber during DAS 56-69 as measured at canopy height. Values for PPF were measured twice per week using a line quantum meter. Symbols: CT – walk-in chamber with control temperature setpoint of 23/18°C; HT1 – reach-in chamber with high temperature set point of 28 / 23°C; HT2 – reach-in chamber with 28 / 23°C; LT1 – reach-in chamber with low temperature set point of 18 / 13°C; LT2 – reach-in chamber with low temperature setpoint of 18 / 13°C

Chamber	PPF µmol m^{-2} s^{-1}	Tday °C	Tnight °C	CO_2 µmol mol^{-1}	RH %
CT	505.7 ± 7.07	23.0 ± 0.4	17.9 ± 0.6	1109 ± 116	84 ± 5
HT1	464.4 ± 20.6	27.2 ± 1.9	22.2 ± 2.9	980 ± 220	94 ± 2
HT2	512.8 ±-58.2	26.9 ± 1.4	22.4 ± 0.2	920 ± 354	85 ± 9
LT1	508.3 ± 33	19.0 ± 0.5	12.6 ± 0.6	1005 ± 227	88 ±6
LT2	464.5 ± 29.4	18.5 ± 0.6	12.9 ± 0.2	1109 ± 549	96 ± 2

Production scheduling data was organized according to maturity date (i.e., time required for the first five fruits to reach breaker stage for each temperature treatment), individual fruit dry mass and size, and the harvest window (defined here as the number of days required to obtain an equal number of fruit for each treatment group for each harvest stage). Significant differences between LT or CT and HT groups were observed with regards to maturity date. An average of 87.6 days was needed for HT fruits to reach breaker stage, 92.1 days was needed for CT fruits and 93.0 days was needed for LT fruits (Table 2). Differences in individual fruit size and dry mass were not observed until the breaker + 3 stage, where LT fruit were larger than CT or HT treated groups (Table 2). Harvest window measurements showed no significant differences among treatments. No differences were found in above ground vegetative mass for plants from different treatments (data not shown).

Table 2: Production scheduling results for maturity date (DAS), individual fruit dry mass (g $fruit^{-1}$) and diameter (cm) per treatment group (HT – pooled high temperature; LT – pooled low temperature; CT – control temperature) per harvest stage.

	Maturity Date[1]		Breaker				Breaker + 3				Breaker + 6			
			Dry weight		Diameter		Dry Weight		Diameter		Dry Weight		Diameter	
HT	87.6	a	17.55	a	8.27	a	14.45	b	7.71	b	15.90	b	7.82	c
CT	92.1	b	15.03	a	8.11	a	13.28	b	7.66	b	17.29	b	8.34	b
LT	93.0	b	17.77	a	8.31	a	18.56	a	8.57	a	21.51	a	8.93	a

Means in the same column followed by different letters are significantly different ($p \leq 0.05$) based on Fishers LSD procedure.

[1] Maturity date was defined as average time required for the first 5 fruits to reach breaker stage for each temperature treatment group.

Quality parameters included the content in soluble and total solids, pH, titratable acidity, consistency of homogenate (Bostwick), L*, a*, b* color indexes, and texture. Tests for starch, ascorbic acid and lycopene content were planned but not completed at the time of this writing. Mean separation results between treatments for several quality factors were summarized in Table 3 per physiological age of the fruit. Statistical results for differences within treatment groups due to harvest stage are listed in Table 4 for the same factors.

Table 3: Statistical differences for temperature treated fruit for three different fruit quality parameters at (i) breaker, (ii) breaker plus three, and (iii) breaker plus six days of harvest.

(i) Fruit Quality Index at Breaker Stage

	Soluble Solids (Brix scale)		pH (pH units)		Acidity (% lactic acid)		Bostwick Consistency		Color a*		Firmness Force	
HT	6.00	a	4.23	a	0.73	a	20.26	a	-0.82	a	25.53	b
CT	5.70	b	4.19	a	0.69	ab	15.94	b	-1.85	ab	27.23	a
LT	5.69	b	4.20	a	0.68	b	16.52	b	-4.3	b	28.93	a

(ii) Fruit Quality Index at Breaker Stage + 3 days

	Soluble Solids		pH		Acidity		Bostwick Consistency		Color a*		Firmness Force	
HT	6.33	a	4.20	a	0.68	a	18.66	a	22.9	a	14.19	b
CT	6.11	a	4.20	a	0.65	ab	19.09	a	19.12	ab	14.63	b
LT	6.18	a	4.24	a	0.62	b	17.16	a	17.96	b	17.01	a

(iii) Fruit Quality Index at Breaker Stage + 6 days

	Soluble Solids		pH		Acidity		Bostwick Consistency		Color a*		Firmness Force	
HT	6.73	a	4.17	b	0.68	a	18.08	a	29.8	a	11.32	b
CT	6.31	b	4.19	b	0.63	b	18.13	a	27.7	b	11.58	b
LT	6.33	b	4.31	a	0.60	b	15.59	b	26.5	b	12.98	a

Means in the same column followed by different letters are significantly different ($p \leq 0.05$) based on Fishers LSD procedure.

Table 4: Within temperature treatment quality differences due to harvest stage (length of vine ripening)

	Soluble Solids			pH			Acidity			Bostwick Consistency			Color a*			Firmness Force		
	HT	CT	LT	HT	CT	LT	HT	CT	LT	HT	CT	LT	HT	CT	LT	HT	CT	LT
B	a	a	a	a	a	a	a	a	a	a	a	ab	a	a	a	a	a	a
B+3	b	b	b	a	a	a	b	b	b	ab	b	a	b	b	b	b	b	b
B+6	c	b	b	a	a	b	b	b	b	b	b	b	c	c	c	c	c	c

Means in the same column followed by different letters are significantly different ($p \leq 0.05$) based on Fishers LSD procedure.

Discussion

Based on results from this single experiment, the two-week perturbation in air temperature had a small but significant impact on production scheduling. Plant maturity was hastened for the HT group representing an average 4-day increase in fruit ripening (the time required for five fruits to reach the breaker stage from each treatment group). The 5°C decrease from the CT thermocycle was not enough to significantly alter fruit ripening for the LT group. Fruit size was also impacted by temperature change, but not until later stages (B+3 and B+6) of vine ripening,

with LT fruits larger than HT or CT fruits (Table 2). Differences in fruit size within each temperature treatment group were also evaluated at each harvest stage (data not shown). Only the LT group showed differences in harvested fruit size, with fruits harvested at the B+6 stages larger than either B+3 or B. This suggests that there is still fruit expansion occurring during the vine ripening period and that there may be some advantage in allowing fruits to ripen as long as possible on the vine prior to harvest when treated with cooler temperatures. This observation assumes that removal of individual fruit from each cluster did not impact carbohydrate partitioning to other fruit in the same cluster that were harvested at a later date.

Because of the sampling method used in harvesting fruit at different physiological stages from the same plant, data was not pooled for measurements of the total yield per plant. Based on the individual fruit size measurements, however, one would expect that the total yield per plant would be increased for the cooler temperature treated fruits (Table 2). Subsequent experiments were designed to provide this information. It would be interesting from a production perspective to determine whether differences in time of application during the growth cycle, duration of the application, and/or magnitude of the temperature change will have a greater impact on production scheduling. The results from this first experiment suggest that application of short term changes in air temperature is a promising method of providing growers with more control of tomato production scheduling during the production process. When considering this approach, temperature effects may be related to other variables, including plant assimilate and water status (Ho, 1996).

There were significant differences in fruit quality parameters between (Table 3) and within (Table 4) treatment groups at the three harvest stages. As expected, differences were found for the same parameters within a treatment group as the duration of vine ripening increased (Table 4). This information illustrates how quality factors change with ripening time for fruit from each treatment group. For example, the color a* index and firmness measurement are significantly different at each stage (Table 4). In general, differences become more pronounced in between treatment groups LT, CT, and HT as time of vine ripening increased from breaker stage (Table 3 (i)), breaker plus 3 days (Table 3(ii)), and breaker plus 6 days (Table 3(iii)). HT treated fruits harvested at breaker stage had higher soluble solids content, acidity, and viscosity (Bostwick consistency), but had a lower number in the firmness test than LT or CT fruits (Table 3 (i)), these differences being beneficial or not depending on the type of handling treatments the tomatoes will be subjected to. These parameters are frequently used to rate the tomato fruit for its fresh consumption, processing and storage properties. As the length of vine ripening increased to the B+6 stage, differences also appear for pH and acidity (Table3 (ii),(iii)). Experiments designed with a larger differential between treatment and control temperatures would be important to provide additional information on the extent to which a temperature perturbation could be used to alter fruit quality.

Fruit skin color is frequently used by growers to estimate the physiological age of the fruit. The assumption is that harvested similarly colored fruit will have similar ripening characteristics as indicated by internal quality (acidity, soluble solids, consistency, and etc.). In the experiment, fruit exhibiting a 25% reddish hue on the surface of the skin were classified as having attained breaker stage. Note that the quality index for color a* relates to the redness of the sample measured. The results shown in Table 3(i) show that there was no difference in fruit color for HT and CT fruits and LT and CT fruits. Differences in other fruit quality characteristics between fruit harvested at the same vine-ripened stage were therefore due to effects of the temperature treatment and not differences in physiological fruit age. The significant differences between temperature treatment groups reported in Tables 3(i), (ii), and (iii) indicate that the temperature treatments altered the rate at which changes occurred in the external appearance of the fruit (color) and the internal characteristics (such as soluble solids, acidity, consistency, etc.) as

compared to the control group. In other words, fruits at the same apparent age as indicated by color might not have the same internal ripening characteristics if they were subjected to different temperatures during production. This is an important consideration for future production strategies particularly where the fruit is intended for fresh consumption.

Based on these results it appears that altering the temperature for a short period at fruit set may be used to change quality for vine ripened fruits either mediated indirectly through increasing the maturity rate or directly, by affecting enzymatic processes. As with production scheduling, differences in the timing, duration, and magnitude of an applied temperature perturbation can be explored further to provide additional information for control strategy improvement for tomato producers.

Conclusion

A two-week air temperature perturbation applied during tomato fruit-set significantly altered production scheduling and quality parameters of vine ripened tomato fruit. A high temperature treatment (28/23°C) slightly increased maturity rate, but resulted in reduced smaller tomato fruit size at later stages of vine-ripening as compared to low temperature treated (18/13°C) plants. Fruit quality parameters that are important for the taste and processing of the fruit were also affected. It appears that the temperature treatments unequally influenced the rates for external color development of the fruit and the internal development of quality parameters such as consistency and soluble solids. The next replicates of these experiments are continuing to provide more information on the response of the plants to environmental perturbations. Work is also being conducted on incorporating the temperature effects on production scheduling into a modeling tool for development of new environmental control strategies for tomato production.

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